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LEVEL II

12

HUMAN SENSITIVITY TO HIGH FREQUENCY SINE WAVE AND PULSED LIGHT STIMULATION AS MEASURED BY THE STEADY STATE CORTICAL EVOKED RESPONSE

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FOR THE COMMANDER

CHARLES BATES, JR.
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The steady state cortical evoked response shows enchanced amplitude to a visual stimulus which is flickered in the frequency range between 38 Hz and 66 Hz. In this study, amplitude was found to be greatest at one particular frequency of stimulation, with the magnitude of the response to the peak frequency as much as double the amplitude of the surrounding frequencies. While all subjects demonstrated this enhancement, the particular frequency at which it was found varied from subject to subject. The range of peak frequencies was found to be 50 Hz to 56 Hz for the subjects studied. Sine

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wave modulated light produced this effect, while stroboscopic stimuli in the same frequency range did not produce it as clearly. It is hypothesized that this narrowly tuned response may be related to a subject's performance, as well as to other physiological characteristics of the individual. Since this amplitude increase is narrowly tuned, it is suggested that the advantages and disadvantages of stimulating humans at their peak frequency should be determined. Possible uses of this phenomena for studying brain functioning and behavior are discussed.

PREFACE

This report describes basic research into the steady state visual evoked response, especially at higher frequencies. It was carried out under grant AFOSR-79-C-0156 to Wittenberg University, using the facilities of the Air Force Aerospace Medical Research Laboratory in support of AFSC Project 7184, Man-Machine Integration Technology for the Air Force.

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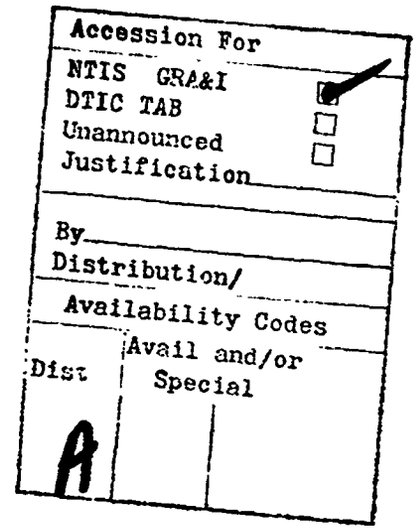

INTRODUCTION

The brain's response to a discrete event, recorded from the scalp and derived from the electroencephalogram (EEG), is called the "evoked response." Averaged evoked potentials (AEP) constitute one way of visualizing such responses triggered by specific environmental events. Two common methods for generating these cranial events are typically employed. In one, the stimulu is presented to the subject at a fairly slow rate (usually less than 1 per second) and the brain events occurring from the onset of the stimulus to a period of up to one second are observed. This technique is called the "transient" evoked response procedure, and is analogous to producing a transient in an electronic system.

In the second method, stimuli are presented to the subject more rapidly, usually faster than 5 per second. Under these circumstances, the brain is not able to reestablish a prestimulus condition prior to the arrival of the next stimulus flash. In this way, a "steady-state" condition is established in which the rapid stimulation causes a repetitive series of responses in the brain. This repetitive action in the brain can be revealed by time-lock averaging of the EEG after each stimulus event. In such cases, the nonconstant events associated with the stimulus are averaged to near-zero, and therefore are not seen in the final average. The result, then, is a waveform with the same dominant frequency as the input stimulus.

Stimulus parameters which are known to influence steady-state AEP amplitude include: frequency (Spekreijse, 1966; Regan 1975) modulation depth (Tweel and Lunel, 1965; Spekreijse, 1966) and color (Regan, 1970 and Regan, 1973). It has been suggested (O'Donnell, 1979) that the demonstrated sensitivity of the steady-state evoked response to such stimulus manipulations makes it a likely candidate for evaluating displays, workspace layouts, and mission workload. Several attempts to apply this measurement technique to field evaluations are currently underway. It is therefore important to investigate the parameters of the kinds of steady-state evoked response which might influence measurements taken in applied contexts. Currently, the Air Force Aerospace Medical Research Laboratory is investigating a number of such parameters. In the course of these investigations, it has become clear that, to be maximally useful in applied settings, it would be desirable to generate the steady-state evoked response with stimuli which are flashing as rapidly as possible. Ideally, if light flashes could be presented above critical fusion frequencies (CFF) the steady-state response could be obtained from an individual in a totally nonobtrusive manner. For this reason, special emphasis has been given to high frequency steady-state evoked responses in AFAMRL.

It is known that a well-formed and reliable steady-state evoked response can be obtained at frequencies above the CFF point (Spekreijse, 1966; Regan, 1968a). These have been described for frequencies at least as high as 90 Hz, and possibly higher (Moise, 1978). Further, three ranges of amplitude maxima have been reported to unpatterned light stimuli; a low-frequency peak centered at about 10 Hz, a medium-frequency peak centered at about 18 Hz, and a high-frequency peak centered in the vicinity of 48 Hz (Regan, 1972). These findings suggest that the human visual system may show temporal frequency sensitivities to particular kinds of stimulation. Further, Regan (1972) mentions in a footnote that individual subjects showed different peak frequencies within these maxima. However, he presents no data on this point, and the commonly presented figure representing the high-frequency component is based upon 2 or 3 subjects and represents grouped data.

Regan also speculates that the peak frequency observed by him, at approximately 48 Hz, may be influenced by the fact that his subjects were Europeans, who were typically exposed to 50 Hz electrical current. He suggests that the peak frequency might be different in areas utilizing 60 Hz electrical systems.

There is need to define the ranges of peak sensitivities of the human with greater precision. One purpose of the present study was to collect high frequency steady-state AEPs from several subjects so that between-subject variability could be estimated, and decisions concerning the appropriate methodology for utilizing steady-state AEPs in applied contexts could be defined. Such data could then be compared with previously reported results.

It is also important for AEP applications to determine the effect of the characteristics of the light source waveform used to stimulate the brain. Most studies in the high frequency ranges have used sine wave modulated light (Spekreijse, 1966; Regan, 1968a). However, other forms of high frequency stimulation, such as stroboscopic light, are available. Stroboscopic stimuli may be more efficient at producing stimulation in the high frequency ranges. The relationship between steady-state AEPs and the type of stimuli is also of considerable theoretical importance. Since the challenge to the visual system introduced by sine wave modulated light is considerably different from that to pulse light, the temporal resolution characteristics of the visual system would be expected to severely influence the final form of this response. It may be possible to infer a great deal about the efficiency of the visual system with particular kinds of stimulation.

A final question of interest concerns the appropriate location of electrodes for obtaining steady-state evoked responses. It is well established that an occipital lead is appropriate for studying basic functioning of the visual system and for investigating and detecting certain pathological states (Regan, 1977). The expanding range of possible applications for this technique raises other questions concerning appropriate sites of electrode placement. In many cases, interactions with cognitive activity would suggest that parietal or central sites might be appropriate. There are little data on the steady-state AEP from these regions. For this reason, steady-state AEPs were recorded from occipital, parietal, and central midline sites in order to permit their comparison, and to see if reliable steady-state AEPs could be obtained from central regions of the human scalp.

METHODS

Six adults (3 females and 3 males) with normal or corrected-to-normal vision served as subjects. Subjects viewed the stimulus setup from a distance of 81.3 centimeters. Sine wave modulated light was produced by two horizontal fluorescent tubes, 23.5 centimeters long and 12.1 centimeters apart. The lamps were driven simultaneously by a Scientific Prototype tachistoscope control, Model GB, modified so that its lamp intensity output could be modulated from an external oscillator. The space averaged luminance of the stimulus, measured from 81.3 cm in front of the fluorescent tubes, was 17.3 foot lamberts at peak. with a modulation depth of 32 percent. For the stroboscopic stimulation, a Grass Model PS22 photo stimulator was used. The face of the strobe light was 13.3 centimeters in diameter, with an average intensity of 4.8×10^3 foot lamberts at the lamp.

Stimuli were presented at 2 Hz intervals between 38 and 66 Hz. Because of artifacts, probably related to 60 Hz activity, three frequencies were omitted from the data collection; 40 Hz, 48 Hz, and 60 Hz. At these frequencies, steady-state evoked responses from subjects were inconsistent and unclear. Accuracy of the stimulus frequency was monitored continuously by a Tektronix Model DC 503 Universal Counter. The order of presentation of the various frequencies was randomized for each subject. Subjects were instructed to fixate on a dot located at the center of each type of stimulus. However, no specific electrooculogram or other eye movement monitor was used to assure fixation.

EEG was recorded from Oz, Pz, and Cz sites, using the 10-20 international electrode system (Jasper, 1958). One mastoid was used for reference, and the other as a ground. Beckman silver/silver chloride elctrodes were used. Electrode resistances were 5K ohms or less. Grass Model P511AC amplifiers with high input impedance probes were used to amplify the EEG. The amplifer filters were set at 1/2 amplitude for 3.0 Hz and 300 Hz; 60 hertz filters were not used. A Nicolet Model CA-1000 was used to average the data. Each channel contained 256 data points, with a sweep epoch of 61.2 milliseconds. Each AEP consisted of the average of 100 samples, triggered on the first stimulus presentation or oscillation after completion of data collection for the previous sample. The first 30 seconds of data were not recorded to assure that the brain had achieved a steady-state condition. Amplitude values were recorded manually and permanent records were provided by X-Y plots.

The testing session typically lasted 90 minutes. Four stimulus conditions, each lasting 3 minutes, were presented consecutively. The subject was then given a 2-to-4 minute break. One longer break, usually lasting 5 minutes, was given in the middle of the testing session. Room lighting was extinguished during the actual stimulation, was was turned on during the break.

RESULTS

Typical steady-state evoked responses from 2 subjects at various stimulating frequencies are shown in Figure 1. Amplitudes were calculated by measuring 2 or 3 peak-to-trough values from each AEP depending on the number of complete cycles in the averaged epoch. These individual measures were then averaged together, and this value was used as the amplitude measure for the AEP.

Individual AEP amplitudes as calculated in the above way are shown in Table 1 for sine-wave modulated light stimulation for each frequency used. The average of the data in this table for the 6 subjects is depicted in Figure 2. In this figure, occipital, parietal, and vertex amplitudes in microvolts are shown as a function of stimulus frequency of the sine-wave modulated light. An overall decline in amplitude with increasing stimulus frequency was evident for all electrode sites. This decline, however, is not monotonic. Amplitudes between 50 and 56 Hz show evident enhancement. Repeated-measures analyses of variance revealed a significant effect due to stimulus frequency ($F = 4.08$, $df = 11/55$, $p < .001$). The enhanced amplitude between 50 and 56 Hz was significant, as indicated by trend analysis, which revealed that the linear ($F = 6.68$, $df = 1/5$, $p < .05$), cubic ($F = 12.30$, $df = 1/5$, $p < .02$), and quartic ($F = 9.32$, $df = 1/5$, $p < .03$) components were significant. The absence of 3 stimulation frequencies was taken into account in the analysis. The peak amplitude range across subjects varied

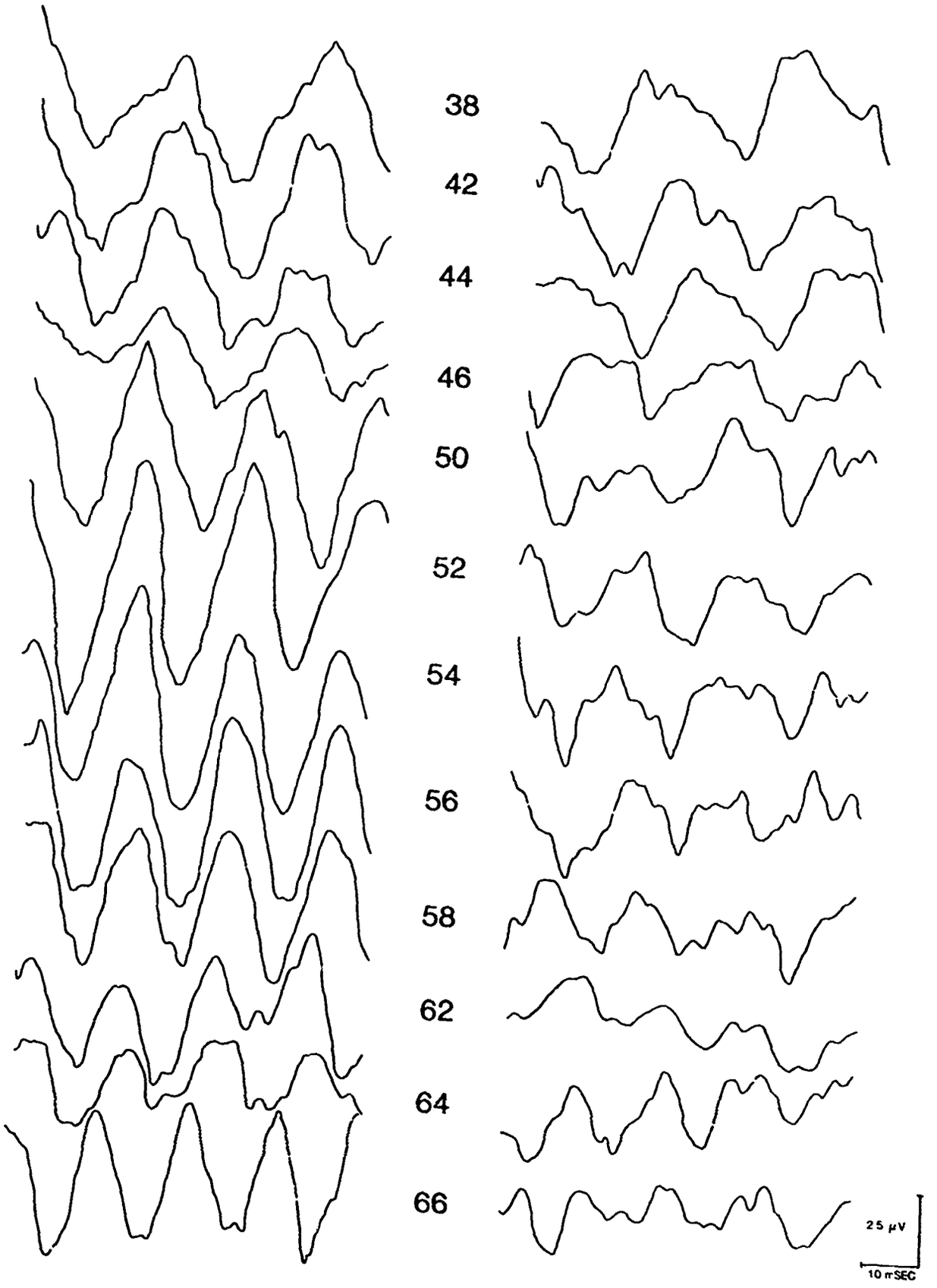

Figure 1. Steady-state AEPs from 2 subjects in response to all of the stimulus frequencies.

Table 1. Individual AEP Amplitudes From Sinewave Stimuli in Microvolts

Subject	Frequency 38	42	44	46	50	52	54	56	58	62	64	66
Occipital (O_Z)												
01	4.2	4.8	3.8	2.5	5.8	7.7	6.6	5.9	5.1	3.8	2.2	4.8
02	6.2	4.5	1.5	3.9	4.0	5.6	3.5	5.3	3.3	3.9	3.0	2.3
03	13.6	8.3	9.9	7.6	5.8	7.4	6.3	7.6	4.7	3.4	3.7	3.1
04	6.0	3.6	1.9	2.0	4.5	3.5	1.8	1.7	0.8	3.0	2.3	2.4
05	5.0	2.9	2.9	2.1	2.3	2.6	2.3	2.1	1.6	2.1	1.8	2.4
06	3.7	3.1	3.0	2.2	2.5	2.4	2.8	2.6	2.3	1.3	1.9	1.7
Parietal (P_Z)												
01	3.9	4.8	4.7	3.9	7.5	8.7	7.6	6.7	5.4	3.9	2.8	6.4
02	6.1	2.8	3.0	3.1	2.0	3.3	2.4	3.1	2.4	3.6	2.3	2.5
03	8.5	4.5	5.3	3.0	2.0	2.3	3.0	4.4	1.8	1.6	1.5	1.9
04	4.0	4.4	1.1	2.0	2.9	1.8	0.9	1.5	1.5	3.1	1.7	1.8
05	4.5	3.0	2.8	1.8	1.6	1.8	2.0	2.0	0.9	1.2	1.3	1.5
06	4.0	4.0	3.4	2.6	3.2	3.0	4.8	3.4	3.2	1.6	1.4	1.9
Central (C_Z)												
01	3.8	3.8	4.7	4.0	5.1	5.3	5.2	4.8	4.7	4.2	3.2	5.3
02	5.7	2.3	1.5	2.4	1.6	2.8	2.7	2.0	2.1	1.7	1.4	2.0
03	3.6	2.7	2.9	1.6	2.1	1.8	1.8	2.6	1.0	0.9	0.8	1.4
04	3.0	2.2	1.7	1.1	1.5	1.1	0.8	1.4	1.3	3.4	1.7	1.0
05	3.6	2.1	1.1	1.4	2.2	1.9	2.2	1.2	1.1	0.9	1.0	0.8
06	3.8	3.7	2.0	2.3	3.1	2.4	5.4	2.8	2.3	1.1	0.9	2.0

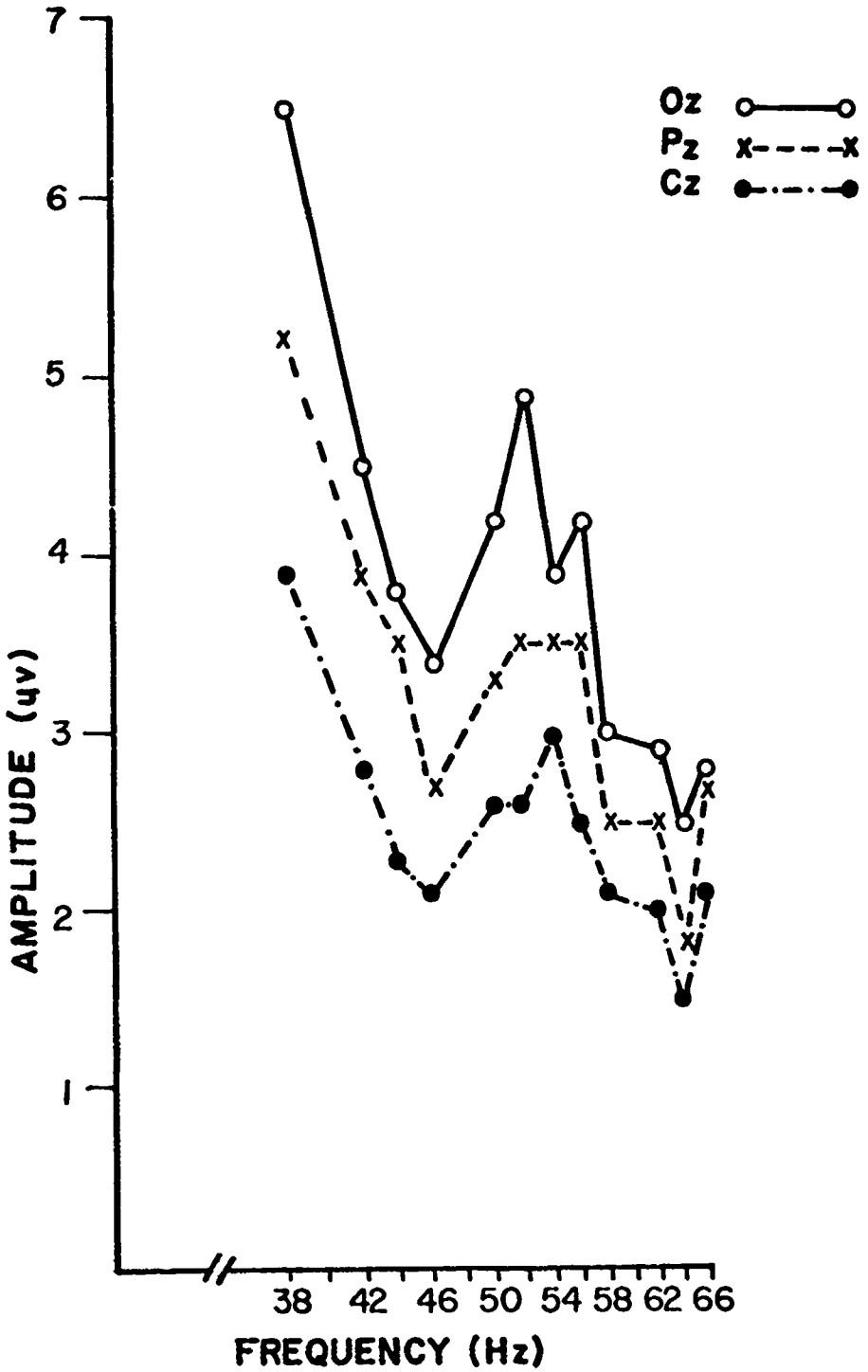

Figure 2. Mean AEP amplitudes derived from sine-wave modulated stimuli as a function of frequency.

from 50 Hz to 56 Hz, with the subjects spread across this range; 50 Hz - 1S, 52 Hz - 3Ss, 54 Hz - 1S, and 56 Hz - 1S.

Data from two subjects are presented in Figures 3 and 4. Each subject produced a definite peak response at a particular frequency. For 1 subject, this frequency was 50 Hz, and for the other it was 54 Hz. All subjects, as shown in Table 1, produced similar peaks. Considering the 6 subjects, the occipital peak amplitude averaged 2.47 microvolts higher than the lowest amplitude found at the frequency below that of the peak itself. Such values indicated that the amplitude response of this steady-state AEP, decreasing in size as frequency increased, showed a sudden rapid increase in amplitude to almost twice the level it had previously reached. Higher frequency stimulation then continued to produce decreasing amplitude evoked responses within these ranges.

The grouped data for stroboscopic stimuli are presented in Figure 5. The same linear decrease in steady-state AEP amplitude with increasing stimulus frequency found for the sine-wave data was evident here. However, there was no enhancement of amplitude anywhere in this frequency band similar to that found with sine-wave modulated light stimulation. Repeated-measures analysis of variance showed a significant effect due to stimulus frequency ($F = 6.16$, $df = 11/55$, $p < .001$). However, trend analysis revealed a significant effect due only to the linear component ($F = 12.72$, $df = 1/5$, $p < .02$). The quadratic component was large, but not significant at the 5% level ($F = 6.07$, $df = 1/5$, $p < .057$). Inspection of individual subject's data, presented in Table 2, revealed the absence of a clear-cut peak sensitivity for anyone within this frequency range.

With respect to electrode sites, AEP amplitude declined generally from posterior to anterior, as one would expect. However, none of these differences were statistically significant for either type of stimulus. In some subjects, as illustrated in Figures 3 and 4, the parietal AEPs sometimes were seen to be larger than the occipital AEP. Thus, although generally larger responses were obtained from the occipital derivation, robust responses were obtained from more anterior locations.

Since female subjects characteristically produce larger amplitude transient AEPs than males (Rodin, et al., 1965), analyses of variance were performed to test for this difference in the steady-state AEP data. No significant difference was found for either the sine-wave or strobe data due to the subject's sex. It must be noted that only 3 females and 3 males made up the sample. The data are, however, suggestive that there may be a difference in the peak frequency for males and females. The males' average peak frequency was higher than the females'; male = 54 Hz, female = 51.3 Hz. The male peak frequencies were: 52, 54 and 56 Hz while the females were: 50, 52 and 52 Hz.

DISCUSSION

These data confirm previous reports suggesting individual differences in the peak amplitude responses to high frequency stimuli. Further, characteristics of these differences across a small sample of subjects were defined. In the present study, there was a 6 hertz range in the point of peak sensitivity between subjects in response to sine wave modulated stimulation, in the band between 38 and 64 Hz.

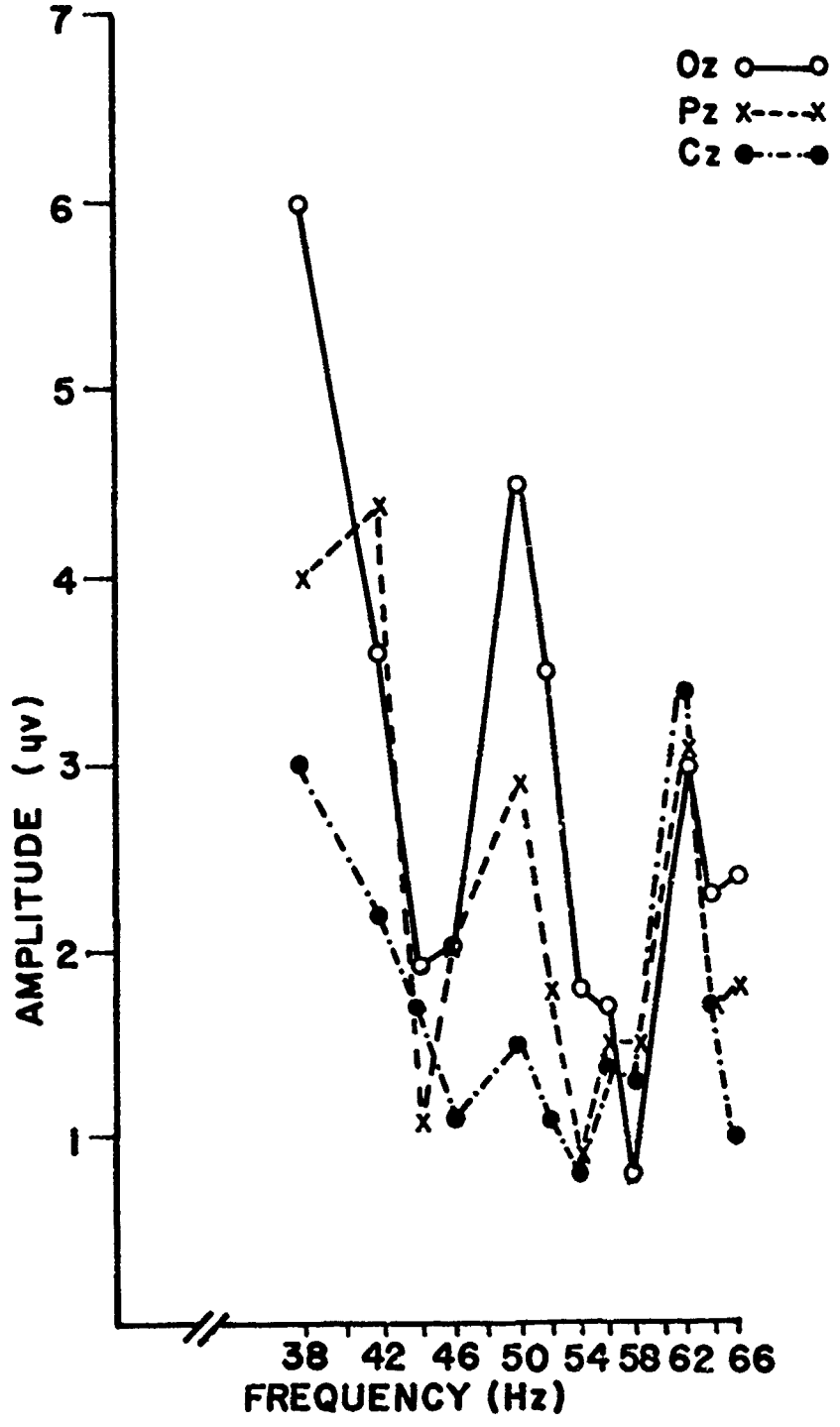

Figure 3. Sine-wave generated AEP amplitudes for subject 04 as a function of stimulus frequency. Note the amplitude peak at 50 Hz.

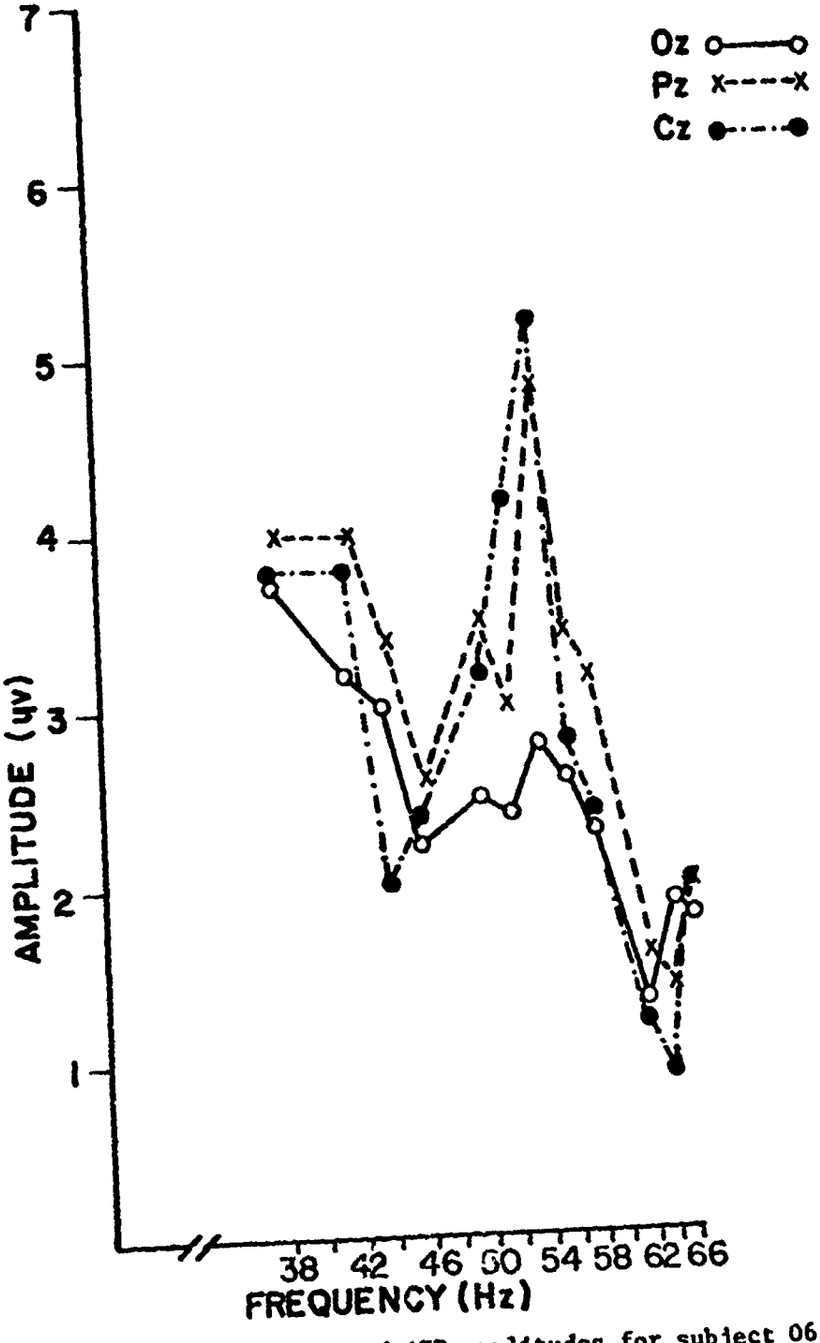

Figure 4. Sine-wave generated AEP amplitudes for subject 06 as a function of stimulus frequency. Note the amplitude peak at 54 Hz.

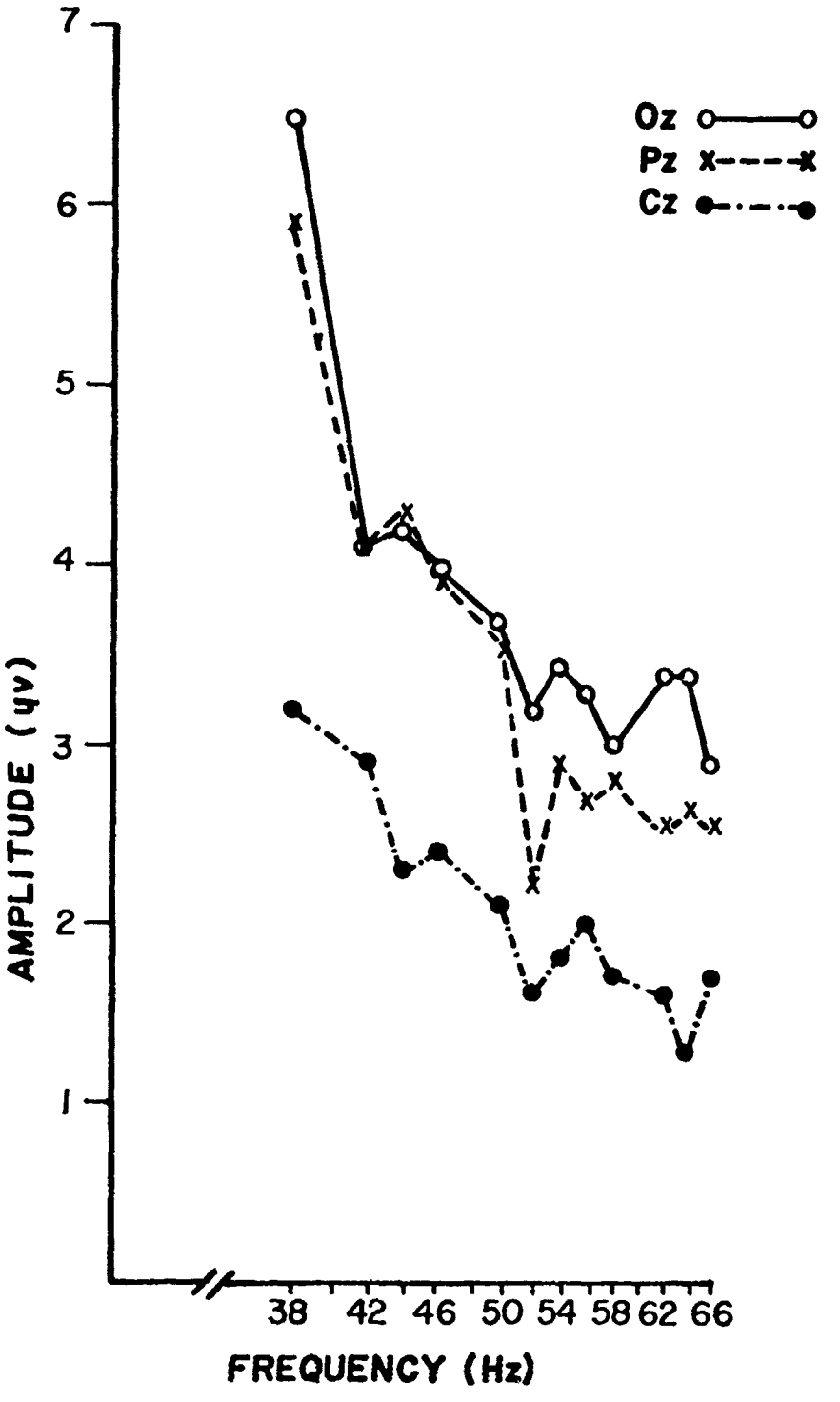

Figure 5. Mean AEP amplitude derived from strobe stimuli as a function of frequency.

Table 2. Individual AEP Amplitudes From Stroboscopic Stimuli in Microvolts

	Frequency											
	Occipital (O_Z)											
Subject	38	42	44	46	50	52	54	56	58	62	64	66
01	5.9	4.4	3.3	2.9	1.8	2.0	3.0	2.6	1.7	2.0	2.4	2.0
02	7.2	4.2	4.7	3.0	4.5	3.7	4.1	3.2	3.1	3.2	3.5	2.8
03	16.4	9.9	10.3	8.6	7.9	5.7	6.6	6.4	7.4	8.7	7.5	6.5
04	3.5	2.5	2.2	3.4	2.3	2.6	2.0	1.9	2.1	2.1	2.0	1.3
05	3.5	2.9	2.5	3.3	2.2	3.3	3.2	2.4	1.8	2.2	2.8	2.9
06	2.7	1.0	1.9	2.9	3.2	1.9	2.3	3.3	1.9	2.1	2.0	2.0
	Parietal (P_Z)											
01	7.4	6.0	6.2	6.0	4.5	3.6	4.6	4.2	4.4	2.7	2.7	3.4
02	7.1	2.1	5.0	2.3	3.5	1.4	2.5	2.4	2.7	3.4	1.9	2.6
03	7.7	8.6	8.0	7.3	4.1	2.7	4.9	2.4	3.1	4.1	3.7	3.3
04	5.3	2.3	2.1	3.4	3.7	2.9	2.7	1.4	2.4	1.2	1.7	0.8
05	2.0	1.1	1.7	2.5	2.9	1.5	1.1	1.6	1.7	1.6	2.4	2.1
06	6.1	4.6	2.8	1.8	2.2	1.3	1.3	4.4	2.6	2.2	3.1	2.9
	Central (C_Z)											
01	2.4	2.5	2.2	3.2	2.7	1.8	2.7	1.9	2.0	1.3	1.3	1.6
02	5.6	2.6	1.8	2.7	2.1	1.5	0.9	1.6	1.6	1.7	0.8	1.6
03	3.7	4.1	4.2	4.5	2.4	1.9	2.3	1.6	0.9	2.4	1.6	2.7
04	1.5	1.0	2.0	1.1	2.7	1.6	2.2	1.1	1.9	1.6	1.4	0.9
05	1.0	2.4	1.6	2.0	1.3	1.7	1.1	0.8	1.4	1.0	1.2	1.5
06	5.2	5.0	2.2	0.7	1.3	1.2	1.3	4.9	2.5	1.4	2.3	1.6

The enhancement of steady-state AEP amplitude at a particular frequency between 50 and 56 Hz was a prominent characteristic of each subject's data, as well as the grouped data. This sensitivity of each individual to a particular temporal frequency was not quantitatively trivial, averaging a doubling of amplitude from levels which it had previously reached. Further, the sensitivity appeared to be very narrowly tuned to a specific temporal frequency. As can be seen in Figures 3 and 4, the peaks are extremely sharp and show clear definition. The reliability of the enhancement effect and the stability of its frequency needs to be ascertained.

From a procedural point of view, these results are extremely important. They indicate that in any attempt to utilize high frequency steady-state evoked responses in applied settings, where grouped data may be used, it is important to determine the peak frequency for each subject. Subjects should then be tested at this peak frequency. If one stimulus frequency is used for all subjects, the interaction with individual sensitivity at particular peak frequencies could confound the results. By locating each subject's highest AEP amplitude frequency, these individual differences can be used to the advantage of the researcher.

The existence of peak temporal sensitivities in the visual system is intriguing from a theoretical viewpoint. Regan (1968a) and Spekreijse (1966) first suggested such temporal frequency sensitivities. One could postulate that such frequencies represent optimal conditions for neural function, much as certain spatial frequencies are processed most efficiently by the visual system It would be interesting to determine if human performance shows either optimization or interference by concurrent stimulation at these peak frequencies. For example, what would be the effect of ambient illumination which was flickering at exactly an individual subject's peak temporal frequency, rather than at the nominal 60 or 120 Hz commonly seen? Would performance be enhanced, degraded, or unaffected? Based on the observation that neural response at these frequencies is maximal, one should certainly see some alteration in performance. The individual differences in peak sensitivity within this frequency range are also of considerable potential interest. It is necessary to determine whether such individual differences are correlated with performance. Do individuals showing peaks at higher frequencies have different transmission characteristics in the nervous system which may result in behavioral differences? From a performance point of view, is it better or worse to have one individual show a higher peak frequency than another?

The data in the present study, in contrast to Regan's (1968a) and Spekreijse's (1966) data, reveal all subjects showing peak frequencies at 50 Hz or above. Regan had speculated that the peak revealed by his subjects might be due to the existence of 50 hertz alternating current in Europe, and he questioned whether subjects continuously exposed to 60 Hz alternating current might show higher peaks. The present results tend to answer this speculation positively. It is a most interesting hypothesis that the differences found between Regan's subjects and those in the present case are due to long-term perceptual effects which result from living with either 50 Hz or 60 Hz systems that affect one's sensitivity to high frequency flicker. It should be noted that, contrary to the data published by Regan (1968a) and Spekreijse (1966), our subjects showed surprisingly large amplitude AEPs at 38 Hz. These authors had found small amplitudes between approximately 20 and 40 Hz. These differences may be procedural, since we began stimulation at the upper end of the band in which they found low amplitudes.

However, such differences should be further explored.

The differences found between male and female peak frequencies are suggestive of sex-related differences in the steady-state AEP. While the amplitudes of the AEPs from male and female subjects were not significantly different, it may be that there are sex-related differences in the peak frequencies. The possibility of differences between the peak frequencies for males and females suggests that further research should be undertaken to test for these differences and their relationship with behavioral traits.

The lack of a clear cut amplitude enhancement within this frequency range to stroboscopic stimulation is a new result. Clearly, the nervous system responds differently to sine-wave modulated light than to stroboscopic light, showing amplitude peaks to the former and not to the latter. AEP differences between these two types of stimuli were not correlated with the subjective perception of flicker. Subjects reported approximately equal flicker perception with both stimuli. However, this lack of correlation is not surprising, since Regan (1968b; Regan and Beverley, 1973) has demonstrated a clear dissociation between AEP amplitude and subjectively perceived flicker.

Obviously, there were considerable differences between the two types of stimuli used in this experiment. The stroboscopic stimulation produced an extremely high intensity, short duration (20 microsecond) flash, followed by complete darkness for a much longer period of time. Thus, modulation depth, as well as the duty cycle of the lamp was significantly different. Graphically, one might consider the temporal course of the strobe light as a series of individual sharp peaks. The sine-wave modulated light, on the other hand, had a modulation depth of only 32%. Further, the effective "duty cycle" was 1:1. Stimulus intensity differences should also be noted. In spite of these rather significant differences, the absolute amplitudes of the AEPs to the two types of stimulation were approximately equal. Thus, the visual/cortical system was capable of resolving both types of stimulation. For some reason, however, the system responded with increased intensity to certain frequencies for the sine-wave stimulation, and not for the strobe stimulus.

One way of viewing this enhanced intensity response might be to postulate that there are cortical units which resonate somewhere in the 50 to 60 Hz range when relatively low modulation, low intensity, and/or equal duty stimulation is provided. Thus, stimulation by sine-wave modulated light permits entrainment of these units. If such speculation can be confirmed, it would mean that the brain contains units which are tuned to this type of stimulation at these particular frequencies. Further, this tuning is specific to stimuli that produce gradual intensity changes, since it is neither found with stroboscopic stimulation nor with alternating checkerboard patterns (Regan, 1977).

If any of the above hypotheses can be confirmed, then it becomes extremely important to determine the characteristics of the "tuned" cortical units. If such units are "adaptive" and can alter their tuning as a result of long-term perceptual experience (exposure to 50 to 60 Hz stimulation), then possibilities for changing the peak sensitivities of an individual might exist. If such changes could be effected, would performance of certain tasks be altered? From a practical point of view, could systems be designed in such a way as to capitalize on the individual subject's sensitivities to temporal frequency stimulation?

Additional questions are raised concerning the interaction of temporal frequency and color. Milner, Regan and Heron (1972) postulate different anatomical sources of steady-state amplitude components. Do color sensitivities also show individual differences correlating with behavior, and could these differences be used in designing color-dependent systems? Finally, it would seem worthwhile to test the utility of high frequency stimulation with strobe light to detect nervous system pathology. Some investigators using stimuli in this frequency range have not found the high frequency AEPs to be sensitive to demyelinating conditions (Heron, Regan and Milner, 1974; Regan, Milner and Heron, 1976). Other investigators have found correlations between high frequency AEPs and pathological conditions (Celesia and Daly, 1977). These reports and the current results suggest that the use of the high frequency AEP should be further studied.

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